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## Cavitation Pitting and Erosion of Al 6061-T6 in Mineral Oil and Water

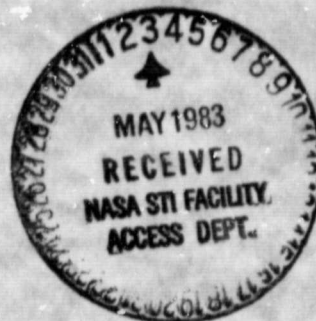
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# CAVITATION PITTING AND EROSION OF ALUMINUM 6061-T6 IN MINERAL OIL AND WATER\*

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## INTRODUCTION

Cavitation erosion in engine bearings has been of increasing importance in the past decade, perhaps, because of the design trends towards higher rotational speeds. The authors are currently carrying out a study of the cavitation erosion of different bearing metals and alloys in mineral oils. This paper presents the variations of weight loss, the pit diameter and depth due to cavitation erosion on Al 6061-T6 in mineral oil and water.

## EXPERIMENTAL EQUIPMENT AND TEST CONDITIONS

The experiments were carried out in an ultrasonic magnetostrictive oscillator operating at 20 K Hz frequency and 50  $\mu$ m double amplitude. The material for the test specimens is taken from commercially pure aluminum Al 6061-T6 rod, 12.7 mm in diameter. The mechanical properties of Al 6061-T6 are presented in Table I. The test liquids are mineral oil, D21 and ordinary tap water whose physical properties are given in Table II.

The test specimen is subjected to cavitation and weight loss measurements are taken at 5 minute intervals for the experiments in mineral oil and at 5 minute intervals, initially, up to a total test time of 35 minutes, and then at 15 minute intervals in water.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Weight loss.

Fig. 1 presents the variations of cumulative weight loss of the test specimen in mineral oil and in ordinary tap water. The corresponding mean depth rate of penetration (MDRP) in the two liquids are presented in Fig. 2. It may be seen from Fig. 1 that the erosion of Al 6061-T6 in mineral oil occurs much faster than in water initially without showing any incubation period. However, as the test time increased, the rate of weight loss or MDRP decreased continuously in mineral oil while the MDRP in water remained approximately constant. This is apparently because of the rapid attenuation of pressure waves in mineral oil as the depth of erosion increased. The peak MDRP in mineral oil is four times the same in water. The eroded surfaces at test times of 40 minutes in mineral oil and at 90 minutes in water are shown in Figs. 3(a) and 3(b) respectively.

### Surface topography

Using a profilometer, surface profiles of the specimen tested in mineral oil were taken at test times of 4, 20, and 40 minutes. The depth of the pits in these measurements varied from 7.5 to 125  $\mu$ m and the top width (diameter) varied from 55 to 450  $\mu$ m. Similar measurements on the specimen examined in water were taken at 20, 60 and 90 minutes. The depth of pits in this case varied from 7.5 to 240  $\mu$ m and the top width (diameter) varied from 55 to 950  $\mu$ m.

\*Presented in greater detail in NASA TP-2146.

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It was observed that the erosion in mineral oil is more uniformly distributed over the specimen surface than in water. For the same amount of erosion, the erosion pits in water are about two times deeper than those in mineral oil, but less in number. The computed mean depth of penetration (MDP) on the specimen examined in water at the end of 90 minutes is 93  $\mu$ m, while the maximum depth of pits measured is 250  $\mu$ m. The computed mean depth of penetration (MDP) on the specimen tested in mineral oil at the end of 40 minutes is 110  $\mu$ m, while the maximum depth of pits measured is 125  $\mu$ m.

### Discussion of experimental results.

(a) Collapse times and pressures. The growth or collapse of the cavitation bubbles occurs during one quarter-cycle of the oscillator, viz. within 12.5  $\mu$ sec. Vyas and Preece (1) reported that a majority of the bubbles collapse in a period of about 5  $\mu$ sec in water. It is known that the viscous effects alter the pressure at the bubble wall and thus act to reduce the effective pressure differential so as to reduce the rates of either bubble growth or collapse. The pressure  $P(R)$  at the bubble wall during collapse may be expressed (2) as:

$$P(R) = P_i(R) - \frac{2\sigma}{R} + \frac{4\mu u}{R} \quad (1)$$

where  $P_i(R)$  = total vapor and gas pressure in the bubble

$R$  = bubble radius

$\sigma$  = surface tension of liquid

$\mu$  = viscosity of liquid

$u$  = bubble wall collapse velocity,  $dR/dt$

$t$  = time

The collapse pressures are generally computed (2) assuming a bubble of initial radius  $R_0 = 1.27$  mm (50 mils). The pressure generated by the collapse of such a bubble to a size  $R/R_0 = 5 \times 10^{-3}$  is  $9.5 \times 10^4$  MPa ( $9.4 \times 10^5$  atm). Vyas and Preece (1) have measured a maximum stress amplitude of  $7.1 \times 10^2$  MPa ( $7 \times 10^3$  atm). If we also assume the same size bubble in mineral oil, the viscosity term in Eq. (1) has a negligible influence on the pressures generated. The erosion pits, however, clearly show that the collapsing bubbles are smaller in mineral oil than in water. Furthermore, the minimum radius  $R$  to which the bubbles collapse would be different in mineral oil and in water. If a bubble of initial radius  $R_0 = 2.54$   $\mu$ m (0.1 mil) collapses to a size  $R/R_0 = 1 \times 10^{-2}$ , the viscosity effect due to the third term on right hand side of Eq. (1) could contribute to as much as 75 percent of the total pressure generated. The pressure generated by such a bubble results in being  $2.52 \times 10^2$  MPa ( $2.4 \times 10^3$  atm). Plesset (3) computed that for bubbles of initial radius  $R_0 \geq 1$  mm collapsing under a pressure of  $(P_0 - p_v) \geq 0.3$  atm, neglect of surface tension and viscous effects introduces an error which is less than 1 percent. The larger weight loss rate initially and the smaller size of pits in mineral oil than the same in water observed in the present studies indicate that

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the cavitation bubbles are smaller in size in mineral oil and that their collapse pressures are, perhaps, higher than the same in water.

## Nature of cavitation pits.

The nature of cavitation pits are generally assumed to be spherical segments as shown in Fig. 4. If  $2a$  is the chord diameter and  $h$  is the depth of pit, the radius  $r_2$  of the sphere may be expressed as:

$$r_2 = \frac{a^2 + h^2}{2h} \quad (2)$$

Using Eq. (2), the radii  $r_2$  of the measured pits are computed. Also, Eq. (2) may be expressed as:

$$\log(h/a) + 1/2 \log(2r_2/h - 1) = 0 \quad (3)$$

Fig. 5 presents the variation of the logarithm of  $h/a$  with the logarithm of  $2r_2/h - 1$ . The relationship between the two parameters is linear. The values of the ratio  $h/a$  are of significance in Fig. 5. In mineral oil, the values of  $h/a$  of individual pits varied from 0.125 to 0.40 while in water, they varied from 0.075 to 0.26. In other words, for the same depth the pits are wider in water than in mineral oil. This, perhaps, is due to the larger size microjets striking the surface in water than in mineral oil indicating that cavitation bubbles grow to a larger size in water than in mineral oil.

Considering pits of a depth of less than 15  $\mu$ m only, it is found that:

$$\begin{aligned} \text{in mineral oil} \quad h/a &= 0.312 \\ \text{and, in water} \quad h/a &= 0.220 \end{aligned} \quad \begin{aligned} (4) \\ (5) \end{aligned}$$

Previous pit measurements by Robinson and Hammitt (4) indicated the ratio  $h/a = 0.20$ . Stinebring et. al. (5) using a microscope and collimated light beam, reported that the minimum and maximum values of  $h/a$  are 0.068 and 0.333 respectively. This range of values is in agreement with the present measurements. Eq. (5) agrees

closely with the measurements of Robinson and Hammitt. A more detailed analysis of the data presented herein can be found in reference 6.

## CONCLUSIONS

1. The maximum weight loss rate or MDRP in mineral oil is four times that in water. But the MDRP reduced continuously with further test time in mineral oil.
2. The cavitation erosion pits are of smaller diameter in mineral oil than the pits in water for the same depth indicating that the cavitation bubbles grow to smaller sizes in mineral oil than in water.
3. Considering pits of depth less than 15  $\mu$ m only, it is found that:

$$\begin{aligned} \text{in mineral oil} \quad h/a &= 0.312 \\ \text{and, in water} \quad h/a &= 0.220 \end{aligned}$$

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TABLE I. - MECHANICAL PROPERTIES OF A1 6061-T6

|  |                    |
|--|--------------------|
| Density, Kg/m <sup>3</sup>                             | 2700               |
| Yield strength, MN/m <sup>2</sup>                      | 110                |
| Ultimate tensile strength, MN/m <sup>2</sup>           | 276                |
| Elastic modulus, MN/m <sup>2</sup>                     | 71x10 <sup>3</sup> |
| Ultimate resilience, MN/m <sup>2</sup>                 | 0.54               |
| EL percent   | 12                 |
| Hardness, Bhn  | 95                 |
| Nominal composition = 0.6 Si, 0.25 Cu, 1.0 Mg, 0.25 Zn |                    |

TABLE II. - PHYSICAL PROPERTIES OF MINERAL OIL AND WATER

| Property                           | Mineral Oil         | Water                |
|------------------------------------|---------------------|----------------------|
| Density, kg/m <sup>3</sup>         | 869                 | 1000                 |
| Kinematic viscosity, at 20° C, cS  | 110                 | 1.01                 |
| Surface tension at 20° C, dynes/cm | 33.2                | 73.6                 |
| Bulk modulus, MPa                  | 1.7x10 <sup>3</sup> | 2.18x10 <sup>2</sup> |
| Flash point, °C                    | 213                 | -----                |
| Pour point, °C                     | -9.4                | -----                |

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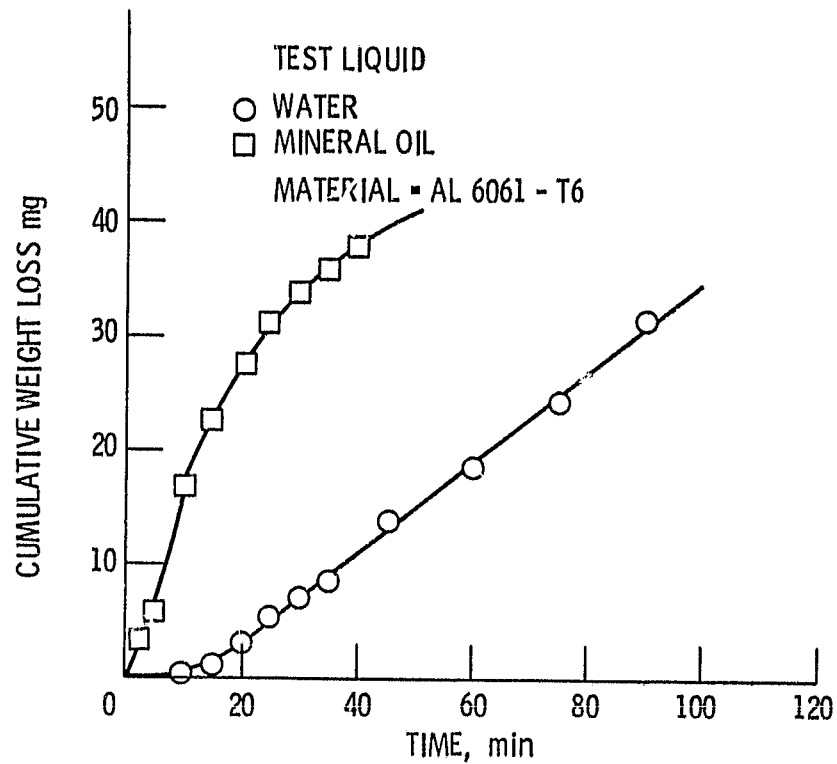


Figure 1. - Cumulative weight loss variation with test time.

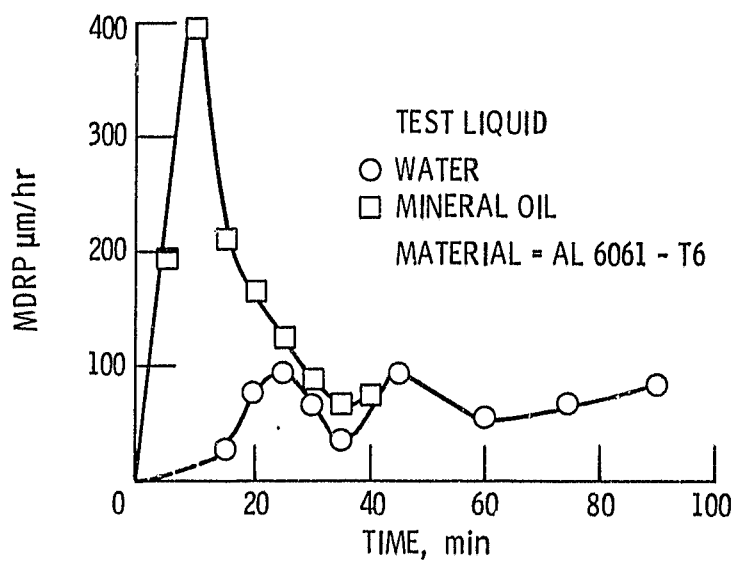


Figure 2. - Mean depth rate of penetration (MDRP) variation with test time.

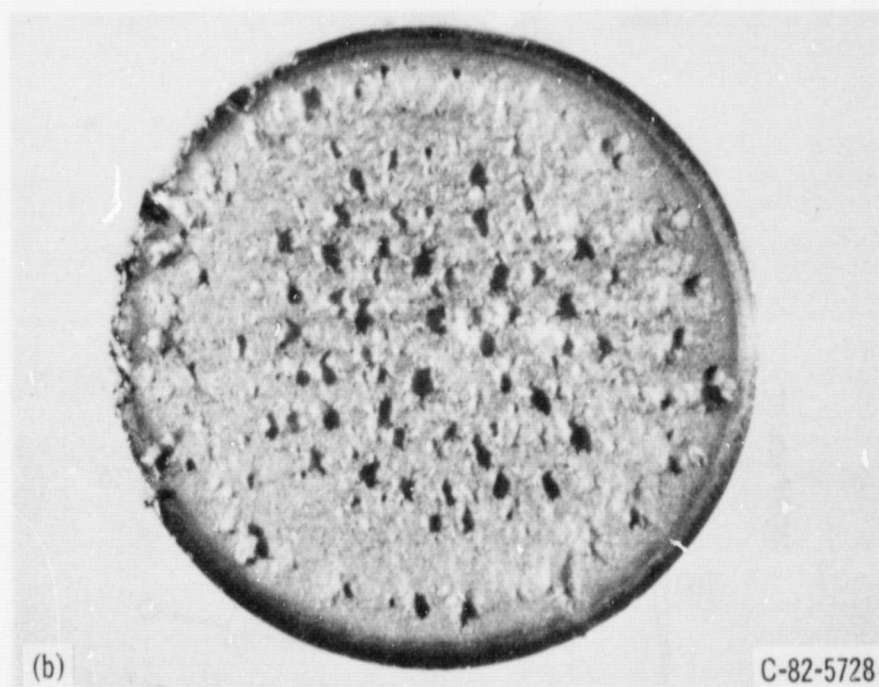
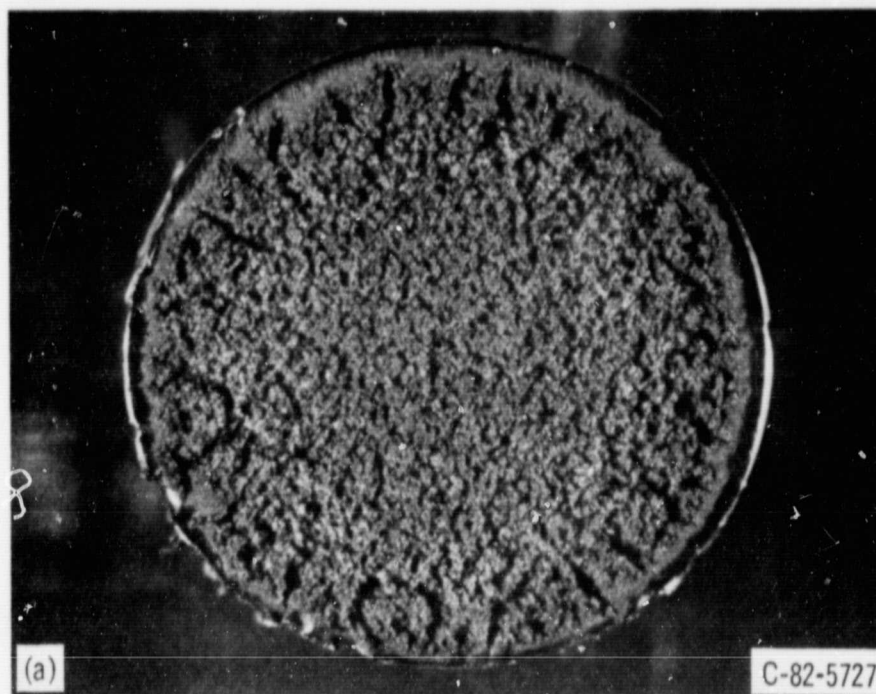


Figure 3. - The eroded surface of AL 6061-T6 (a) at  $t = 40$  minutes in mineral oil and (b) at  $t = 90$  minutes in water.

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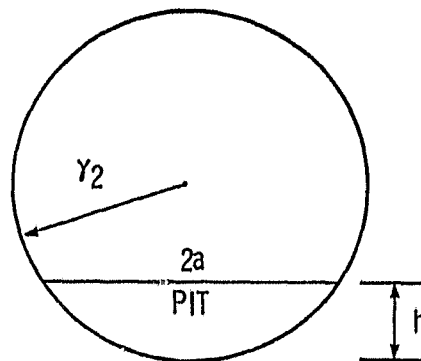


Figure 4. - Theoretical cavitation pit.

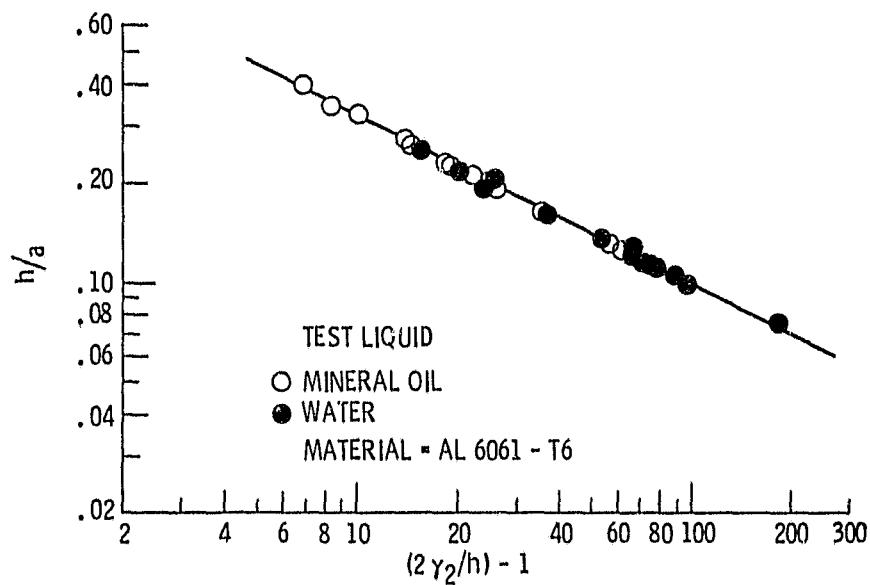


Figure 5. - Variation of logarithm of  $h/a$  with the logarithm of  $2\gamma_2/h - 1$ .